A Strategy for Observing the Moon to Achieve Precise Radiometric Stability Monitoring

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RÉSUMÉ

On présente une stratégie utilisant la Lune pour effectuer le suivi précis de la stabilité radiométrique des capteurs de télédétection en orbite autour de la Terre. La Lune peut être utilisée efficacement en tant que référence d'éclairement constante pour le suivi de la dérive de la sensibilité spectrale de l'instrumentation en orbite en (1) observant la Lune à des angles de phase équivalents, (2) en observant la Lune à des angles de libration observateur-Lune équivalents, (3) en observant la Lune à des angles de libration Soleil-Lune équivalents, et (4) en observant la Lune à des taux de balayage et des angles azimutaux équivalents. Généralement, lorsque l'on peut utiliser des rotations de la plate-forme dans n'importe quel axe pour visionner la Lune près du moment désiré de la phase lunaire, il est démontré que les niveaux d'éclairement de la Lune pour des cycles lunaires choisis peuvent rester compris à l'intérieur de 0.1%, à part de corrections de 1/R2, qui peuvent être déduites de façon précise à partir d'éphémérides. Les effets orbitaux associés aux mouvements de la plate-forme autour de la Terre affecteront le taux de changement de l'éclairement lunaire mais le taux moyen ou représentatif de changement d'éclairement lunaire se situe approximativement autour de 0.1% en 4-5 minutes près de la phase lunaire de 67.5°deg .

La stratégie d'observation lunaire discutée dans ce manuscrit a été développée en vue de l'étalonnage du capteur MODIS (Moderate Resolution Imaging Spectroradiometer) prévu pour installation sur la plate-forme AM-1 de EOS (Earth Observing System). Dans le cadre du programme AM-1, les manoeuvres de la plate-forme seront vraisemblablement limitées à des mouvements de roulis seulement. Compte tenu de cette restriction, la phase lunaire lors des périodes d'observation disponibles pourra varier par rapport à la valeur optimale par jusqu'à 0.46°deg et des corrections de l'éclairement lunaire de plus de 1.1% pourront être nécessaires. L'incertitude liée à ces corrections est estimée à 0.1-0.2%. Si l'on considère les incertitudes introduites par le décalage dû à la libration, la variabilité solaire et le bruit lié au capteur, l'incertitude relative du changement pour deux observations différentes pourra être de 0.2-0.3%.

Sur la base d'un modèle préliminaire d'effets de libration en développement au USGS et utilisant des mesures de la sonde Clementine Lunar Orbiter, l'éclairement lunaire à un angle de phase et une distance solaire donnés peut varier jusqu'a ± 2% dû aux phénomènes particuliers qui sont visibles et qui résultent de la libration lunaire. La réponse du capteur à la source lunaire pour un cycle donné peut être comparée à la réponse équivalente pour d'autres cycles en faisant correspondre les angles de phase lunaire et de libration à l'intérieur de limites spécifiques. Basé sur les résultats du modèle du USGS, on démontre que 48 des 75 cycles lunaires au cours de la période 1994-1999 présentent au moins une correspondance comparable à l'intérieur de 0.1%. Tous les cycles ont au moins une correspondance à l'intérieur de 0.27%. Pour une période donnée de 6 ans, des correspondances multiples sont fréquentes et permettent le suivi périodique de la stabilité et de la tendance avec moins de 1.0% de variation de l'éclairement. La stratégie d'observation proposée est complémentaire à la campagne intensive de mesures lunaires au sol prévue par la USGS dans le cadre du projet EOS (Earth Observation System). Le programme du USGS permettra de faire des comparaisons entre diverses observations.

SUMMARY

A strategy for using the Moon to achieve precise radiometric stability monitoring of Earth-orbiting remote sensors is presented. The Moon can be used effectively as a constant irradiance reference for monitoring on-orbit changes in instrument responsivity by (1) observing the Moon at equivalent phase angles, (2) observing the Moon at equivalent observer-Moon libration angles, (3) observing the Moon at equivalent Sun-Moon libration angles, and (4) observing the Moon at equivalent scan rates and aspect angles. For the general case in which platform rotations about any axis can be used to view the Moon near the instant of the desired Lunar phase, it is shown that Lunar irradiance levels for selected Lunar cycles can be matched to within 0.1 %, aside from $1/R^2$ corrections, which can be precisely determined from ephemeris data.

Orbital effects associated with platform motion around the Earth will affect the rate of Lunar irradiance change. An

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average or representative rate of Lunar irradiance change is about 0.1% in 4-5 minutes near 67.5° Lunar phase.

The Lunar observation strategy discussed in this manuscript was developed to support calibration of the Moderate Resolution Imaging Spectroradiometer (MODIS), to be carried aloft on the Earth Observing System (EOS) AM-1 platform. In the AM-1 program, platform maneuvers are likely to be restricted to rolls only. With this restriction, Lunar phase at available observation opportunities may differ from the optimum value by up to 0.46° and Lunar irradiance corrections of up to 1.1% may be required. The uncertainty associated with these corrections is estimated to be 0.1 - 0.2%. Including uncertainties introduced by Lunar phase correction, libration offset, Solar variability, and sensor noise, relative change uncertainty for two observations is estimated to be 0.2 - 0.3%.

Based on a preliminary model of libration effects developed at USGS from Clementine Lunar orbiter measurements, Lunar irradiance at a given phase angle and Solar distance can vary as much as ± 2% as a result of Lunar libration. Sensor response to the Lunar source in a given cycle can be compared with the corresponding response in other cycles by matching Lunar phase and libration angles to within specified limits. Using results from the USGS model, it is shown that 48 of the 75 Lunar cycles in the 1994-1999 epoch have at least one match comparable to within 0.1%. All cycles have at least one match to within 0.27%. For a given 6 year epoch, multiple matches that enable periodic stability and trend monitoring with less than 1.0% irradiance variation are abundant. The proposed observation strategy is complementary to the anticipated extensive ground-based lunar measurements planned by USGS in support of the Earth Observation System (EOS) project.

Introduction

Since the surface of the Moon is disturbed only by occasional meteorites, the reflectance of the Moon is considered to be very stable (Kieffer 1997a). However, wide changes in Lunar radiance and irradiance occur as the illumination and viewing geometry changes within the Lunar orbit. Radiometric variations have not been precisely measured for the complete cycle of Sun, Earth, and Moon relative positions or at a range of visible and infrared wavelengths adequate to characterize the wavelength response of many remote sensors. This discussion explores the fundamental idea that precise calibration trending of individual remote sensors and precise cross calibrations among multiple sensors can be achieved if key Lunar observation parameters are carefully controlled.

Lunar observation can provide crucial calibration cross-references for the envisioned next generation of smaller, faster to build, and more frequently deployed remote sensing instruments. A four part strategy is proposed for precisely determining the radiometric calibration changes of an individual sensor or relative calibration differences among several sensors:

(1) observe the Moon at equivalent phase angles, i.e. at the same observer-Moon-Sun angle;
(2) observe the same Lunar terrain, i.e. observe at the same Earth-Moon libration angles;
(3) observe the Moon at the same Solar illumination aspect, i.e. at the same Sun-Moon libration angles;
(4) observe the Moon in the same manner, i.e. at equal sensor scan rates, equal scan angles with respect to Lunar illumination, etc.

To the extent that these observation criteria cannot be concurrently satisfied, correction factors can be used to bring observations to a common baseline. Lunar measurements that will help generate the required correction factors are being obtained by Kieffer and Wildey (Kieffer and Wildey 1996). Large correction factors will generally introduce additional uncertainty (~2-4%), and the highest quality comparison between observations will be achieved when the above criteria are closely satisfied and correction factors are minimal. Observed lunar irradiances will be normalized to standard Sun-to-Moon and Moon-to-Earth distances.

Solar output is affected by the number, location and size of Sunspots, plages, active networks, etc. distributed across the face of the Solar disk. While the dynamic processes that contribute to the Solar state at a particular time are quite complex, some regularity in Solar processes does occur, including an 11-year Solar activity cycle expected to reach a maximum in the year 2000. Statistically, Solar variability is maximum when Solar activity is maximum. Solar variability within the spectral bandpass of a particular MODIS band depends on the relative contributions within the bandpass from the Solar continuum, Fraunhofer absorption lines (if any), and discrete emission lines (again if any). Expected long-term secular variations associated with the Solar activity cycle are small, typically of the order of 0.02-0.04%/ year at the wavelengths corresponding to the MODIS spectral filters. Over the projected life of the MODIS instrument (1998-2004), aggregated secular variations may amount to perhaps 0.1%. Maximum short-term Solar variations occur when an occasional large active region comes into view; short-term variations are expected to reach a maximum at a Solar activity maximum. In the year 2000 expected short-term changes range from 0.11% to 0.17%. Short-term changes are largest at the blue end of the spectrum (Schatten 1995).

Strictly speaking, the requirement to precisely reproduce the conditions of an earlier Lunar observation at a later viewing could be interpreted to mean that the images to be compared must be coregistered on a pixel-by-pixel basis. For many remote sensing instruments, including MODIS, the requirement to reproduce the pixel boundaries of an earlier observation at a later date would pose a significant platform attitude control problem. Just as important, if sensor response is compared on a pixel-by-pixel basis, changes in sensor Point Response Function (PRF) could be falsely interpreted as a change in instrument responsivity, particularly in regions near high-contrast features such as the Lunar boundary. At present, it appears that the resolution of both of these issues is to compare images on the basis of total integrated response to the Moon and not on the basis of individual pixel response. By this approach, the Moon is used as an irradiance standard and not a radiance standard. Analysis on a pixel-by-pixel or radiance basis may be useful as an adjunct technique for detecting on-orbit changes in sensor Point Response Function.

The second section of this report is a general description of the view geometry expected for Lunar observation through the MODIS space view port. MODIS will view the Moon at a nominal phase angle of 67.5°, and illustrative computations were done for this Lunar phase angle. The third section of this paper examines the rate of change in Lunar phase angle and the corresponding change in Lunar irradiance that occurs in time interval Δt. This information relates directly to adjustment factors used to refer Lunar observations made at somewhat different phase angles to the same phase angle baseline [Criterion (1) above]. The fourth section examines issues relating to the concurrent satisfaction of Criteria (1), (2), and (3). Lunar viewing opportunities that satisfy Criterion (1) exactly and Criteria (2) and (3) well enough to provide a Lunar irradiance match to within a small fraction of a percent are discussed in this section. This section includes graphical charts depicting Lunar observation opportunities. Overall results are summarized in the fifth section.

The Lunar View through the MODIS Space View Port

The MODIS sensor scans in the plane perpendicular to the nominal EOS platform velocity vector. With the platform at the nominal operating attitude, a space view port located on the starboard side of the instrument provides a sensor space view beginning 10.83° above the orbit normal and ending 6.77° from the normal. (See **Figure 1**.) As the platform advances in its orbit, the scan across the space view port sweeps over the annular region shown in the figure. The center of the annulus rotates once per year along a path near the ecliptic, and on several occasions each year, the orbit of the Moon will cross the annular region and the Moon will appear in the MODIS space view port with no adjustments in platform attitude. Small departures from nominal platform attitude increase the number of Lunar viewing opportunities and allow the adjustment of Lunar view parameters to consistent values best suited for sensor response comparisons. Platform attitude manoeuvers involving rolls of 10° or 15° are considered feasible.

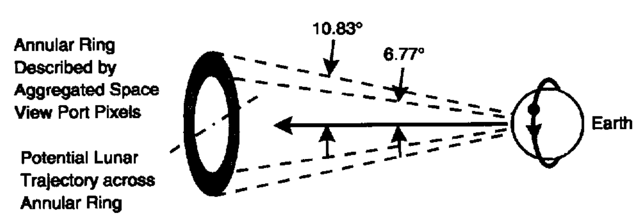

Figure 1.
The annular region of space swept out over an EOS orbit by the MODIS sensor looking through the space view port. The sensor scans in the plane perpendicular to the platform velocity vector. The annular ring is centered on the orbit normal.

The EOS AM-1 platform will be launched in a 10:30 AM orbit as shown in **Figure 2** (at equator crossing, the platform is offset 1.5 hrs × 15deg/hr = 22.5° before local noon). The orbit normal (center of the annular region) is therefore offset about 22.5° with respect to the Last Quarter Moon (90° Lunar phase angle) and the approximate expected Lunar phase angle for nominal-attitude space view port observations (with no platform attitude manoeuvers) is 90° − 22.5° = 67.5°. Given a 10.83° maximum offset from the center of the annular region, the Lunar phase angle for nominal-attitude views can range from about 56.67° to about 78.33°.

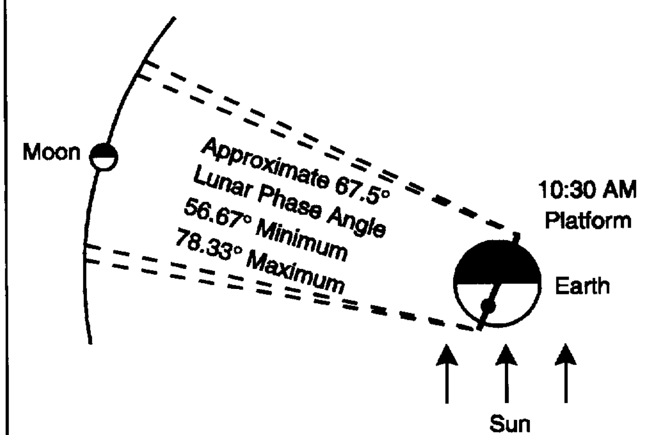

Figure 2.
Relationship of the Earth and Moon to the Solar incident direction in the MODIS space view port Lunar view configuration. Because of the 10.83° maximum radius of the annular region, actual Lunar phase can range from about 56.67° minimum to about 78.33° maximum for nominal-attitude Lunar views requiring no platform roll.

Lunar Irradiance Change Rate

Phase-related uncertainty in Lunar calibration can be related to the change in Lunar irradiance that occurs during an arbitrary time interval Δt. A two-step procedure was used to compute the rate of Lunar irradiance change in this analysis. The first step relates Lunar irradiance to Lunar phase angle. Irradiance measurements obtained by Lane and Irvine (Lane and Irvine 1973) provide the basic relationship between observation wavelength, Lunar phase angle, and Lunar irradiance. A second-order, two-dimensional interpolation between measured data points supplied by Lane and Irvine was used to obtain Lunar irradiance as a function of observation wavelength and phase angle. The second step of the analysis relates Lunar phase angle to time. In this analysis, the approximate relation

$$\frac{d\phi}{dt} \doteq \frac{2\dot{A}}{r^2} - \frac{2\pi}{Y_S} \quad (1)$$

was used, where ϕ is the observed Lunar phase angle, t is time, $\dot{A}$ is the (constant) areal sweep rate of the vector from the Earth to the Moon as defined in Kepler's second law of planetary motion, r is the Earth-Moon separation, and Y_S is the sidereal year.

Two numbers are computed from Equation 1, phase change rates when r is a minimum (perigee) and when r is a maximum (apogee). Equation 1 ignores high order terms in the Lunar orbit and the eccentricity of the Earth's orbit.

Irradiance change depends on the observation wavelength, and in this analysis, results were obtained for all MODIS bands within the scope of the Lane and Irvine measurements ($0.359\ \mu m \leq \lambda \leq 1.06\ \mu m$). **Table 1** is a tabulation of the MODIS bands covered, the wavelengths of these bands, and the average relative Lunar irradiance change occurring in a 10 minute interval (percent). Effects are similar for all bands, but MODIS band 9 (0.443 µm) is most affected and MODIS Bands 4, 11, and 12 (0.555 µm, 0.531 µm, and 0.551 µm, respectively) are least affected. **Figure 3** is a plot showing the general behavior of Lunar irradiance change as a function of elapsed time. These results show that time offsets corresponding to half an AM-1 platform orbit period generate phase angle adjustment factors of about 0.9-1.3%. To obtain adjustment factors of 0.1%, Lunar observations must occur within about 4 - 5 min. of optimal times.

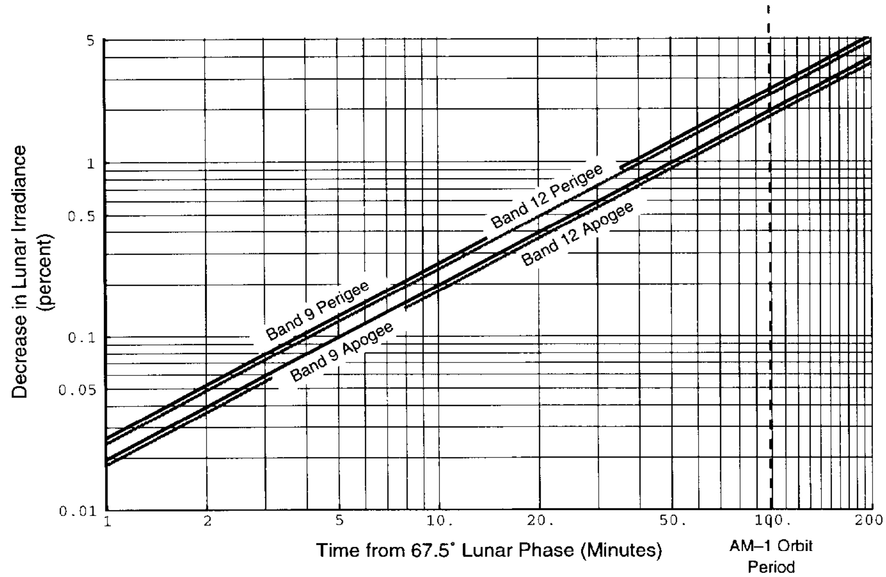

Figure 3.
Relative Lunar irradiance change as a function of elapsed time at a Lunar phase angle of 67.5°. Results are given for the times when the Moon is closest to the Earth (perigee) and for the times when the Moon is furthest from the Earth (apogee). Results depend on the wavelength (MODIS band) selected. At 67.5° phase angle, change is maximum for MODIS Band 9 (0.443 µm) and minimum for Band 12 (0.551 µm). Changes for all other VIS/NIR bands are between the dark and lighter gray lines.

Table 1.
Relative change in Lunar irradiance at 67.5° phase occurring in a 10 min. interval for MODIS bands shorter than 1 micron. To obtain phase adjustment factors less than 0.1%, Lunar observations must occur within about 4 - 5 min. of optimal times.

MODIS Band No.	Wavelength (µm)	Average Change 10 min. (%)
1	0.645	0.229
2	0.858	0.228
3	0.469	0.229
4	0.555	0.213
8	0.412	0.228
9	0.443	0.230
10	0.488	0.223
11	0.531	0.213
12	0.551	0.213
13	0.667	0.229
14	0.678	0.229
15	0.748	0.228
16	0.869	0.228
17	0.905	0.226
18	0.936	0.224
19	0.940	0.224

Libration Effects on Lunar Irradiance

Because the average period of the Moon's rotation around its rotational axis exactly equals the average period of its revolution around the Earth, the Moon always presents nearly the same side to an Earth observer. Small departures from the same-side phenomenon do occur, however. Since the Lunar equator is inclined 6° 41' with respect to the plane of the Moon's orbit around the Earth, at maximum inclination an Earth observer can see 6° 41' beyond the Lunar north or south pole. Likewise, because of the eccentricity of the Lunar orbit around the Earth, the rotation of the Moon around its rotational axis does not exactly match the angular advance of its revolution around the Earth, and additional portions of the Moon become visible at the Lunar east or west limb. The effective angular offset of the visible Lunar surface due to this effect can be as large as 8°.

The angular offsets affecting the portion of the Lunar surface visible to an observer are called Lunar libration angles. The concept of a *sub-observer* and *sub-Earth point* is used to describe libration quantitatively. Imagine a straight line drawn from an observer to the center of the Moon. The point where the line crosses the Lunar surface is called the sub-observer point. The sub-observer point is at the center of the apparent Lunar disk seen by the observer. The selenographic [or Lunar] latitude (b_0) and longitude (l_0) of the sub-observer point provide a quantitative measure of the observer's libration. Corresponding quantities for a hypothetical observer located at the center of the Earth define geocentric libration. In this analysis, the Lunar latitudes and longitudes defining geocentric libration will be designated b_E and l_E, respectively.

For a satellite orbiting the Earth, the difference between observer-referenced and geocentric libration can be as much as a degree, and the effect of observer offset must be considered. For MODIS, however, all Lunar calibration observations will be done on the dark side of the Earth and libration differences due to platform motion will be much less than a degree. In this exploratory analysis, observer-referenced libration and geocentric libration have been treated as equivalent quantities. The current analysis demonstrates feasibility of proposed techniques. However, Lunar calibration opportunities depend on instrument orbit parameters and the specific Lunar cycles that are available for comparison (related, in turn, to the launch date and working life of the instrument to be calibrated). The calibration parameters given in this report must be specifically computed for the instrument and epoch of interest.

Geocentric Lunar libration angles are tabulated in astronomical almanacs. Libration angles for this analysis were obtained from a computer-based almanac called the *Multiyear Interactive Computer Almanac* or *MICA* (U.S. Naval Observatory 1990). *MICA* was prepared by the U.S. Naval Observatory and the latest version available (version 1.0) covers the decade from 1990 - 1999. **Figure 4** is a plot obtained from *MICA* showing geocentric libration at 67.5° Lunar phase angle as a function of lunation number during the period 1994 - 1999. (A lunation is the period between successive new Moons.) Seventy-five lunations occur during the 6-year interval studied in this analysis. The dates and times (UT1) corresponding to 67.5° Lunar phase angle are tabulated for each of the 75 lunations in **Table 2**. Observer-referenced libration angles provide a unique mathematical measure of the Lunar features included in the apparent Lunar disk.

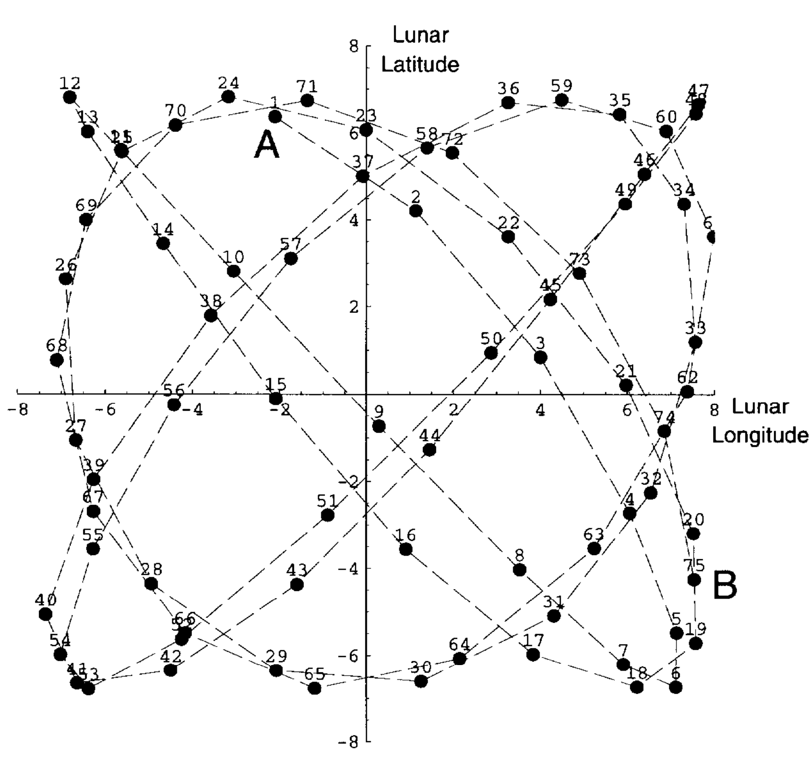

Figure 4.
Lunar libration plot showing the geocentric libration of the Moon at 67.5° Lunar phase angle. Each circular dot represents the libration for a single lunation (time period between successive new Moons) at the time during that lunation when the phase angle reached 67.5°. Successive lunations during the 1994 - 1999 time period are numbered sequentially beginning with 1 and ending at 75. The dashed lines connecting the dots in the figure indicate Lunation sequence and do not portray libration at phase angles other than 67.5°. The plot begins at the dot marked with the letter A and ends at the dot near the letter B.

In analogy with observer-referenced libration, a straight line can be drawn from the center of the Sun to the center of the Moon to define a *sub-Solar point*. Solar illumination relative to the Moon can be characterized by the location of the sub-Solar point as was done for the Earth-based observer. **Figure 5** is a plot showing the location of the sub-Solar point as a function of lunation number. While the longitude changes of the sub-Solar point are similar to those of the sub-Earth point, latitude changes of the sub-Solar point are

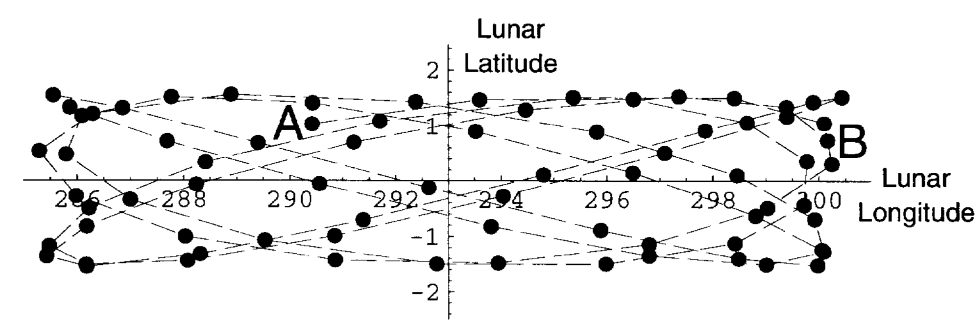

Figure 5.
Lunar libration plot corresponding to Figure 4 showing the Solar-referenced libration of the Moon at 67.5° Lunar phase angle. Solar-referenced libration in the vertical dimension is caused by the small angular offset between the Lunar equator and the ecliptic (1° 32'.5). The effect is similar to the seasonal change in Solar elevation on Earth except that the Lunar effect is much smaller.

Table 2.
Dates and times (UT1) when the geocentric Lunar phase angles reaches 67.5° for the six-year interval between January 1994 and December 1999. Data obtained from the *Multiyear Interactive Computer Almanac* (*MICA*) prepared by the U.S. Naval Observatory.

Lun. No.	Date			Time (UTI)	Lun. No.	Date			Time (UTI)
001	1994	Jan	03	06:50:28.7	041	1997	Mar	30	00:38:41.8
002	1994	Feb	01	15:10:54.5	042	1997	Apr	28	09:00:51.0
003	1994	Mar	02	23:34:00.9	043	1997	May	27	15:02:11.7
004	1994	Apr	01	08:37:07.3	044	1997	Jun	25	20:03:35.9
005	1994	Apr	30	18:43:17.5	045	1997	Jul	25	01:22:32.0
006	1994	May	30	06:19:38.2	046	1997	Aug	23	08:12:27.5
007	1994	Jun	28	19:53:21.4	047	1997	Sep	21	17:40:34.3
008	1994	Jul	28	11:37:59.2	048	1997	Oct	21	06:43:12.0
009	1994	Aug	27	05:12:45.2	049	1997	Nov	19	23:44:55.3
010	1994	Sep	25	23:36:05.3	050	1997	Dec	19	20:11:23.2
011	1994	Oct	25	17:27:37.6	051	1998	Jan	18	18:04:40.5
012	1994	Nov	24	09:38:15.5	052	1998	Feb	17	14:57:01.6
013	1994	Dec	23	23:28:41.7	053	1998	Mar	19	08:53:34.3
014	1995	Jan	22	10:49:36.9	054	1998	Apr	17	23:05:28.4
015	1995	Feb	20	19:56:18.5	055	1998	May	17	09:35:31.6
016	1995	Mar	22	03:27:06.5	056	1998	Jun	15	17:02:55.2
017	1995	Apr	20	10:15:36.3	057	1998	Jul	14	22:32:19.7
018	1995	May	19	17:28:04.4	058	1998	Aug	13	03:19:24.1
019	1995	Jun	18	02:09:45.6	059	1998	Sep	11	08:54:36.6
020	1995	Jul	17	13:15:51.2	060	1998	Oct	10	16:47:20.0
021	1995	Aug	16	03:17:16.6	061	1998	Nov	09	04:07:43.0
022	1995	Sep	14	20:06:29.2	062	1998	Dec	08	19:24:06.1
023	1995	Oct	14	15:00:39.9	063	1999	Jan	07	14:01:16.6
024	1995	Nov	13	10:50:40.0	064	1999	Feb	06	10:34:54.5
025	1995	Dec	13	06:07:09.7	065	1999	Mar	08	07:16:00.0
026	1996	Jan	11	23:19:43.2	066	1999	Apr	07	02:26:22.4
027	1996	Feb	10	13:13:32.5	067	1999	May	06	18:48:07.7
028	1996	Mar	10	23:30:22.8	068	1999	Jun	05	07:41:32.3
029	1996	Apr	09	06:49:51.8	069	1999	Jul	04	17:10:45.0
030	1996	May	08	12:30:16.2	070	1999	Aug	03	00:03:21.5
031	1996	Jun	06	18:00:32.5	071	1999	Sep	01	05:34:50.0
032	1996	Jul	06	00:37:46.6	072	1999	Sep	30	11:17:54.1
033	1996	Aug	04	09:28:43.2	073	1999	Oct	29	18:38:40.1
034	1996	Sep	02	21:13:23.3	074	1999	Nov	28	04:34:36.3
035	1996	Oct	02	12:16:23.5	075	1999	Dec	27	17:33:22.6
036	1996	Nov	01	06:36:31.3					
037	1996	Dec	01	03:23:25.2					
038	1996	Dec	31	00:50:34.4					
039	1997	Jan	29	20:35:01.6					
040	1997	Feb	28	12:43:00.2					

much smaller. Changes in the sub-Solar point are much less since the angle between the Lunar equator and the ecliptic is 1° 32.5'. Changes in the elevation angle of the Sun relative to the Lunar horizon are in direct analogy to seasonal changes in the elevation angle of the Sun on Earth, except that "seasonal" effects on the Moon are much smaller. Solar-referenced libration angles provide a quantitative measure of the Solar incidence direction relative to the Moon.

Results from a preliminary model of geocentric libration effect being developed at the United States Geological Survey (Kieffer 1997b) were used to compute irradiance changes corresponding to the geocentric librations shown in **Figure 4**. The libration model relates irradiance deviation at 67.5° phase (in percent) to geocentric libration latitude and longitude; tabular results obtained from the model are presented in **Table 3**. The model is based on Lunar images obtained by the Clementine Lunar orbiter early in 1994. The Clementine UVVIS sensor is a 384 × 288 pixel CCD camera covering 0.415 - 1.0μm in six spectral bands. By controlling the attitude (look direction) of the platform and the time of observations, images were obtained at a variety of Solar illumination and observation angles. Images corresponding to a given Solar illumination and Lunar look direction were combined into a mosaic and aggregated to 8 km resolution. Composite values obtained from the mosaic were then integrated over the face of the Lunar disk to obtain total Lunar irradiance as a function of Solar incidence and look directions. Irradiance change values are based on the assumption that Solar-referenced libration is held at 0° and Solar-referenced longitude is adjusted to maintain a constant Lunar phase angle of 67.5°.

A three-dimensional plot of the USGS irradiance change data is given in **Figure 6**. A two-dimensional third-order interpolation was used to obtain the smooth surface shown in the figure. Note that the primary change in Lunar irradiance occurs as the Lunar latitude of the sub-Earth point changes. **Figure 7**

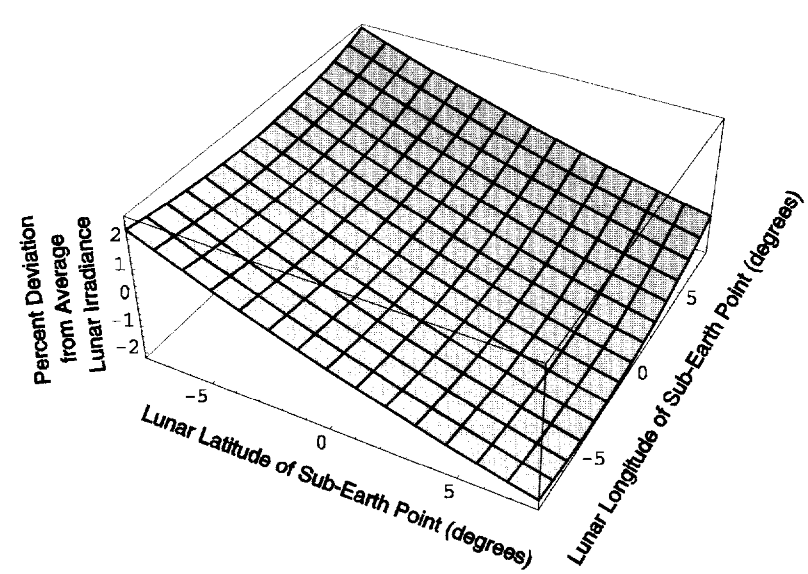

Figure 6.
Interpolated plot obtained from the Lunar irradiance data in Table 2. The ordinate is relative Lunar irradiance change in percent (Kieffer 1997b).

Table 3.
Percent deviation from average Lunar irradiance as a function of geocentric libration latitude and longitude at 67.5° Lunar phase angle. Solar-referenced libration latitude is held at 0° in the table and Solar-referenced longitude is adjusted to maintain a constant phase angle of 67.5°. Results are from a preliminary model of libration effects provided courtesy of USGS (H. Kieffer 1997b).

	Longitude						
Latitude	-7.5°	-5.0°	-2.5°	0.0°	2.5°	5.0°	7.5°
-7.5°	2.10	1.87	1.73	1.70	1.80	2.02	2.39
-5.0°	1.32	1.09	0.96	0.96	1.07	1.33	1.72
-2.5°	0.58	0.37	0.25	0.26	0.41	0.68	1.11
0.0°	-0.10	-0.30	-0.41	-0.38	-0.21	0.09	0.54
2.5°	-0.73	-0.92	-1.00	-0.96	-0.77	-0.44	0.02
5.0°	-1.30	-1.47	-1.54	-1.48	-1.28	-0.93	-0.45
7.5°	-1.82	-1.97	-2.02	-1.94	-1.73	-1.37	-0.87

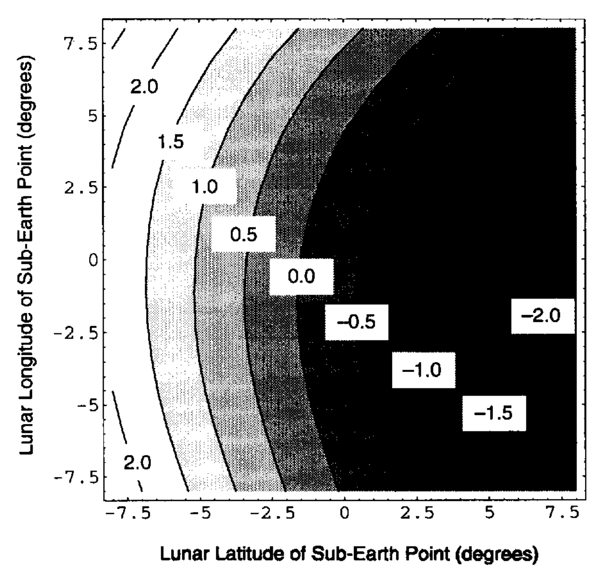

Figure 7.
Constant irradiance contours representing the data of Figure 6. The label attached to each contour gives relative Lunar irradiance change in percent. Lunar irradiance changes are greater for changes in libration latitude than for changes in Lunar longitude (Kieffer 1997b).

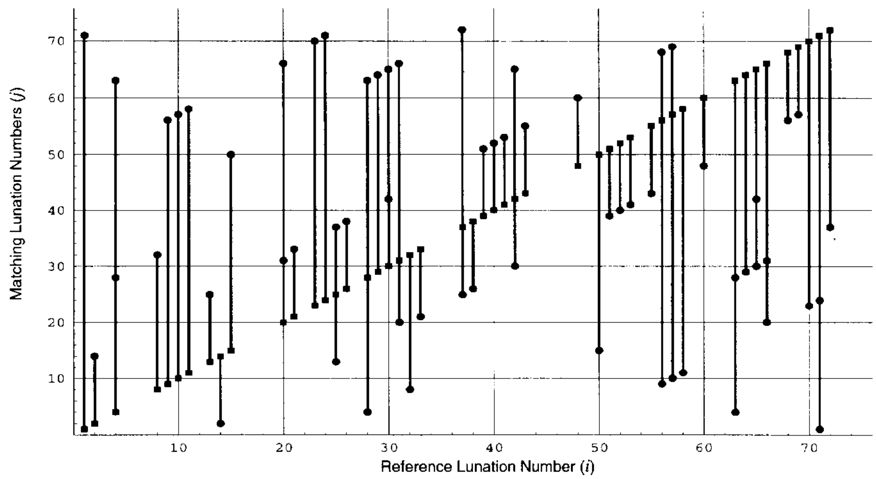

Figure 8.
Cross-reference matrix for Lunar calibration. The ordinate shows Lunar cycle numbers satisfying $|E_i - E_j| \leq 0.1$ % where E_i and E_j are the Lunar irradiance of Lunar cycles i and j, respectively, i is the Lunation number of the reference Lunar cycle (square) and j is the corresponding Lunation number of other matching Lunar cycles (circles). Note that each "matching" pair appears twice in the chart: once with the lower numbered Lunation of the pair listed as the reference, and once with the higher numbered Lunation listed as the reference. Dates and times corresponding to Lunation numbers are given in Table 2. All irradiances are determined at 67.5° Lunar phase angle. In the six year (75 Lunation) interval depicted, 64% of the Lunations have at least one match to within 0.1%.

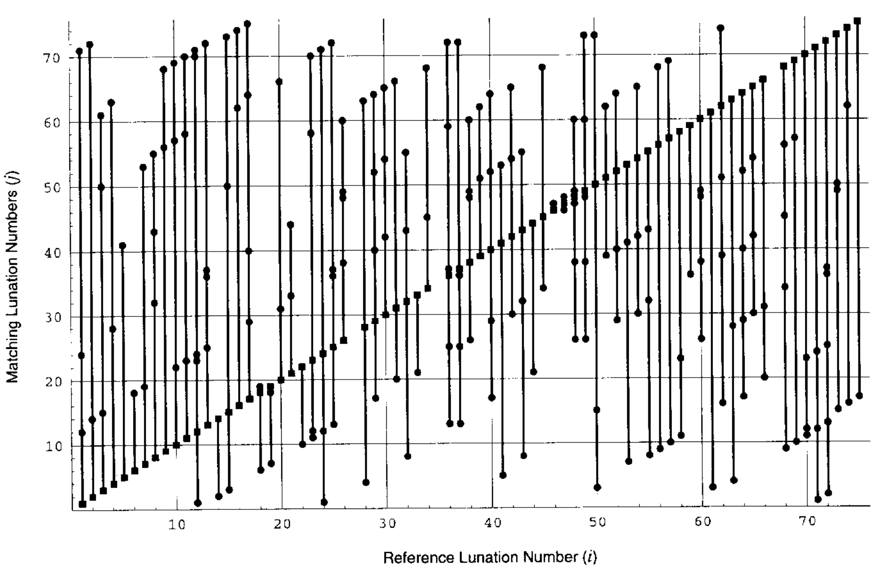

Figure 9.
Cross-reference matrix for Lunar cycles satisfying $|E_i - E_j| \leq 0.2$ %. Ninety-six percent of the Lunations have at least one match to within 0.2%.

is another plot of the same data showing constant irradiance contours as a function of geocentric libration latitude and longitude. Assuming that the Lunar irradiance change due to Solar-referenced libration is the same as that due to geocentric libration, the combined effects of Solar-referenced libration and geocentric libration were obtained as the root-sum-of-squares (RSS) of the individual libration effects. "Matched" Lunation sets were then selected from among the 75 Lunar cycles listed in **Table 2** by setting a difference threshold Δ_{cutoff}, i.e. designating the Lunar irradiance for cycle i by E_i and for cycle j by E_j, Lunation pairs i and j were selected such that

$$|E_i - E_j| \leq \Delta_{cutoff} \tag{2}$$

where Δ_{cutoff} represents the Lunar irradiance consistency required for successful calibration cross-reference. Computations were done for Δ_{cutoff} equal to 0.1%, 0.2%, 0.5%, and 1.0%; results are presented graphically in **Figures 8, 9, 10** and **11**, respectively. Each of the Lunar cycles was sequentially selected as the reference cycle for that comparison (index i and irradiance E_i in (2)) and the E_j for each of the remaining cycles was considered against the requirements of (2). The reference cycle is represented by a square in the figures, and matching Lunar cycles are represented by circles. It is apparent that more than one circle may correspond to a given square. At the 0.1% and 0.2% levels, a few Lunar cycles have no matches. Examination of the data shows that 48 of the 75 Lunar cycles have at least one match to within 0.10%, 72 have at least one match within 0.20% and all cycles have at least one match to within 0.27%. **Figure 11** shows that numerous opportunities exist at the 1% level.

Conclusions

Properly arranged Lunar observations can be used to monitor on-orbit changes in remote sensor response. Lunar calibration observations taken at 67.5° Lunar phase angle can be matched to achieve about a 0.1% difference in Lunar source irradiance among specific sets of Lunar cycles selected for calibration comparison. In the 75 Lunar months occurring during the six year period considered (1994 - 1999), 48 Lunar months or 48/75 = 64% of the Lunar months provide at least one calibration comparison with a Lunar source irradiance match to within 0.10%. Seventy-two out of 75 or 96% of the months provide a best match to within 0.20% and all (or 100%) of the months provide at least one calibration comparison with a Lunar irradiance match to within 0.27%. For

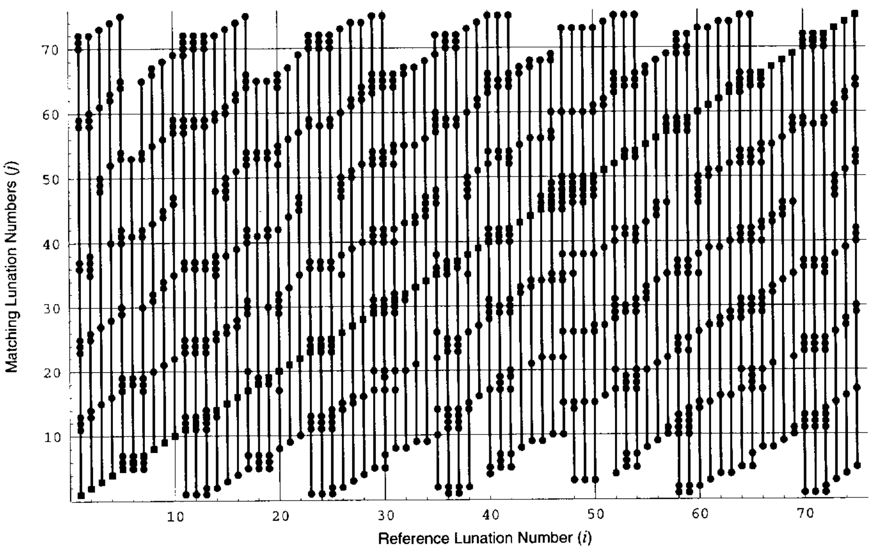

Figure 10.
Cross-reference matrix for Lunar cycles satisfying $|E_i - E_j| \leq 0.5$ %. All Lunations have at least one match to within 0.27%

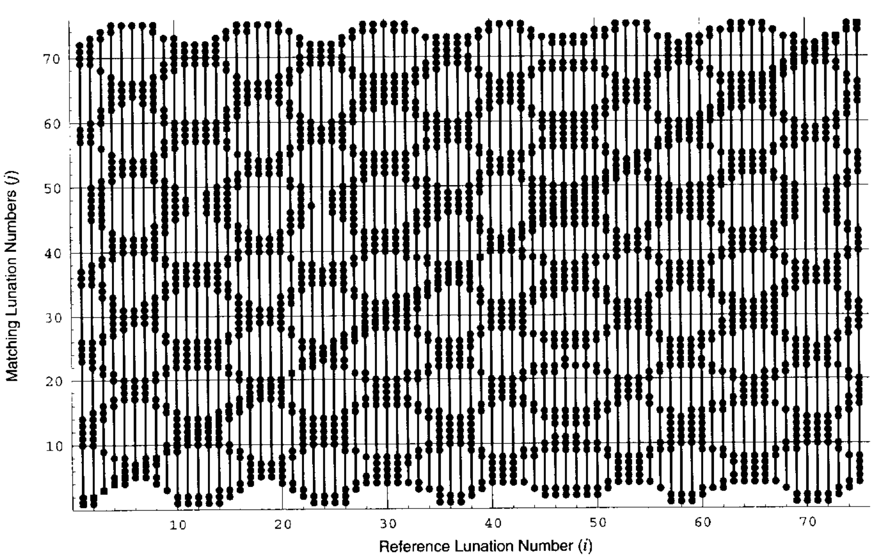

Figure10.
Cross-reference matrix for Lunar cycles satisfying $|E_i - E_j| \leq 1.0$ %. Irradiance matches to within 1% are abundant.

the 1994 - 1999 epoch, matches that enable periodic stability and trend monitoring with less than 1.0% irradiance variation are abundant. Including uncertainties introduced by Lunar phase correction, libration offset, Solar variability, and sensor noise, relative change uncertainty for two MODIS observations will be perhaps 0.2 - 0.3%. While MODIS parameters were used in this analysis, similar results are expected for other remote sensing instruments.

References

Kieffer, H.H. and R.L. Wildey. 1996. "Establishing the Moon as a Spectral Radiance Standard", *Journal of Atmospheric and Oceanic Technology*, Vol. 13, No. 2.

Kieffer, H.H. 1997a. "Photometric Stability of the Lunar Surface", submitted to *ICARUS* April 16, 1997

Kieffer, H.H. 1997b. Private communication.

Lane, A.P. and W.M. Irvine. 1973. "Monochromatic Phase Curves and Albedos for the Lunar Disk", *The Astronomical Journal*, Vol. 78, No. 3

Schatten, K.H. 1995. "Solar Spectrum Model for Inflight Calibration of the MODIS Reflective Bands", Internal memorandum, Goddard Space Flight Center, Greenbelt, MD, September 5, 1995.

U.S. Naval Observatory. 1990. "MICA for MacIntosh--User's Guide: An Interactive Astronomical Almanac for 1990--1999 from the U.S. Naval Observatory", National Technical Information Service, Washington, D.C.